Feedback and Control Course Labs for Distance Learning

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Abstract:

Classic Feedback and Control is an undergraduate course that introduces students to concepts and methods for modeling, analysis, and design of single-input-single-output feedback control systems in the Electrical and/or Computer Engineering majors. In addition to using lectures to explain theories and assigning homework assignments for students to practice their modeling and analyses skills, instructors would usually supplement the course by a series of hardware-based experiments and software-based simulation labs so that students can apply the acquired knowledge to physical systems and real-world control problems.

Similar to many other institutions, our ECE program offers a Feedback and Control course to junior students in the Electrical Engineering and Electromechanical Engineering majors. This course is a 3-hour lecture, 2-hour lab, as a 4-credit course. Topics discussed include modeling in both the time and the frequency domains, time response, model reduction, stability, steady-state error, root locus, design via root locus, frequency response, and design via frequency response.

Due to the COVID-19 pandemic, both students and faculty in our institution were forced to work and study from home in summer 2020. In order to engage students in distance learning, application-oriented and active-learning opportunities were created. A series of exclusively software-based labs and projects were designed to help students gain a better understanding of how the knowledge are useful in real-world situations. Particularly, nine simulation labs and two simulation projects were used in the class of summer 2020.

In order to evaluate the effectiveness of the designed simulation labs and projects in helping students to grasp and then apply the control concepts and ideas, surveys were conducted in the summer 2020 class to collect students' opinions and feedbacks. Among the 27 participating students, 81.4% of students "agree" or "strongly agree" that simulation laboratory exercises increased their interest in the subject, 85.1% of students "agree" or "strongly agree" that simulation laboratory exercises helped them better to learn course content, and 77.7% of the students thought simulation laboratory exercises were excellent or very good.

We also compared the percentage of students who performed at the A, A-, B+, B, and B- levels with past records (while teaching was in-person), which turned out to be comparable and similar. This indicates the effectiveness of these simulation-based labs & projects, and their contribution in helping to maintain the course standard.

Introduction

In many institutions, undergraduate courses in Feedback and Control for engineering students are usually at the junior level. Such courses provide students an introduction to concepts and methods related to modeling, analyses, and control of a physical system. Typical topics covered include Laplace transform, modeling in the frequency domain, time response, model reduction, stability, steady-state errors, root locus, design via root locus, frequency response, and design via frequency response. Feedback and Control courses are usually considered to be complex,

abstract, theoretical, and mathematically-involved that can be hard for many undergraduate students to fully understand [1-4]. Students find it difficult to relate the discussed topics with their daily lives [1-4]. Common pedagogy involves theory with lectures and readings, mathematical homework assignments, and exercises with computer simulations and hardware-based experiments. In this course the concepts are difficult for the students to visualize, and most students have no conscious personal experience with the phenomena [1-4].

At our institution, junior students in Electrical Engineering and Electromechanical Engineering take a Feedback and Control course to acquire a strong foundation for more advanced subjects, such as industrial controls. The course has prerequisites in Differential Equations and Motors & Control. Due to the COVID-19 pandemic, all in-person courses were transitioned to remote instructions in the summer 2020. It was the first 100% distance-learning semester for both faculty and students in our institution.

Many students were worried that their academic success might be affected since there were so many external factors that distracted them from staying focused and motivated. It was thus the challenge faced by almost all instructors to make distance learning still "work" for as many students as possible [5-8]. For courses with hardware-based designs and projects, different approaches were adopted to provide hands-on components to students during the pandemic. Some institutions tried to "maximize/optimize lab time" by live-streaming and asking students to share their experience with their remote team members [9]. Others chose to send design kits to students' homes [10], or designed computer-based simulation projects as alternative project and lab exercises [11]. Most instructors realized and agreed that students' enjoyment is very important [12]. If students enjoy their courses, they are more likely to stay active, motivated, and engaged [7]. One common practice to improve motivation and learning is to create application-oriented, hands-on active-learning opportunities for the students [1-4]. Along this track, a series of software-based simulation labs and projects with clearly-stated objectives were developed and used in the classroom activities in summer 2020.

This paper describes a series of software-based simulation labs & projects that were developed to facilitate teaching and learning in a junior-level Feedback and Control course under e-learning. The effectiveness of these simulation methods was confirmed by students' feedback (collected via a survey) and comparison with past records. Similar performance was obtained during distance learning as compared with in-person teaching in the past.

Design of Software-Based Simulation Exercises

The Feedback and Control course discussed in this paper is for junior-level students in Electrical Engineering and Electromechanical Engineering. This course is a 3-hour lecture, 2-hour lab, for a 4-credit course. Lectures and labs were conducted synchronously through Zoom virtual meetings in summer 2020. The following topics were addressed, including modeling in the frequency domain, modeling in the time domain, time response, model reduction, stability, steady-state errors, root locus, design via root locus, frequency response, design via frequency response.

As with any teaching, a course must begin with clearly articulated learning objectives [6]. The course learning objectives include:

1. Develop and use models of physical systems in forms suitable for use in the analysis and design of control systems.
2. Analyze the time and frequency domain responses of first and second order systems to various inputs.
3. Determine the stability of closed-loop control systems.
4. Apply root locus and frequency response (Bode plot) techniques to analyze and design control systems.
5. Demonstrate proficiency using application software and hardware for analysis and design of control systems.
6. Demonstrate understanding of the Z-transform and digital control systems.

Due to distance learning, all labs and projects were software-based (particularly, MATLAB and Simulink based) simulation exercises. Students did each lab individually. Table 1 shows the nine labs and the objective of each lab. Table 2 shows the two projects and their objectives.

Table 1. List of Labs and Objectives

Labs	Lab Objectives
Lab #1: MATLAB Basics	• To become familiar with basic MATLAB commands • To become familiar with MATLAB Simulink
Lab #2: Identification of a 2nd Order Underdamped System from Its Step Response	• To perform system identification of a 2nd order underdamped system from its step response.
Lab #3: Second-Order Approximation for a Higher-Order System	• To understand the 2nd-order approximation for a higher-order system • To practice inverse Laplace transform
Lab #4: Reduction of Multiple Subsystems	• To analyze response of a system consisting of multiple subsystems • To reduce multiple subsystems to a single equivalent system
Lab #5: The Effect of Increasing the Gain	• To understand the effect of varying the gain in the closed-loop system • To be familiar with commonly-used MATLAB commands that helps for analysis & design
Lab #6: Stability via Routh Hurwitz Criterion	• To analyze stability of a system consisting of multiple subsystems by Routh Hurwitz Criterion
Lab #7: Design of PID Controllers	• To design PI, PD, and PID controllers using Root Locus
Lab #8: Frequency Response Based Lead-Lag Compensator Design	• To design Lead, Lag, Lead-Lag compensators based on frequency response (Bode plot).
Lab #9: Digital Control Systems	• To use MATLAB commands and Simulink to simulate digital control systems.

Lab 1 made sure students know how to develop and test systems in MATLAB Simulink. Lab 2-9 allowed students to apply the concepts and knowledges that they learned in the lectures to analyze, design, and verify systems by simulation.

The purpose of the projects was to allow the students to apply the basic technology that they learned in the labs to more advanced and practical challenges.
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Table 2. List of Projects and Objectives

Projects	Project Objectives
Project #1: Modeling and Design of Operational Amplifier (OA) Circuits	- To be able to model a physical system, for example, an operational amplifier (OA) circuit - To be able to analyze the performance specifications of a 2nd-oder underdamped system - To be able to design a controller to alter the system's behavior according to design specifications - To be able to realize the designed controller using, for example, operational amplifiers - To be able to use MATLAB for simulation, analysis, design and verification.
Project #2: Modeling and Control of DC Motor	- To be able to model a physical system, for example, a DC motor. - To be able to analyze the performance specifications of a 2nd-order system. - To be able to design a controller to alter the system's behavior according to design specifications. - To be able to use MATLAB for simulation, analysis, design and verification. - To be able to understand the effect of sampling on digital control systems.

For Project 1, the system shown in Figure 1 was given. Students were asked to design a controller using root-locus-based design methods such that the settling time can be reduced by half while maintaining the original damping ratio.
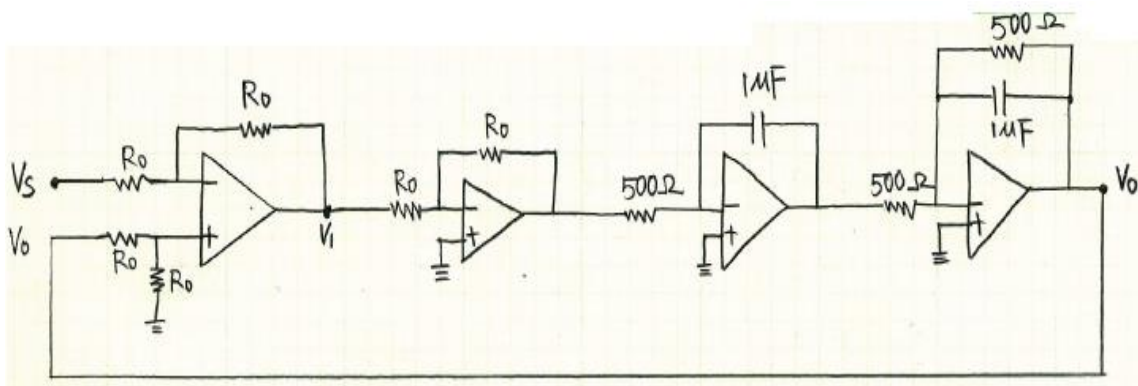

Figure 1. Project 1 system

Typical steps of Project 1 are described as follows:

1. Frequency-domain modeling of the Original System.
2. Simulate the original circuits to make sure that the model obtained in Step 1 is correct.
3. Analysis of the Original System: Analyze the original system by finding its closed-loop transfer function, poles of the closed-loop system, settling time, percentage overshoot.
4. Controller Design: Design of a controller to satisfy the design specifications based on root locus.
5. Realization of the Designed Controller using Operational Amplifiers: Realize/Implement the designed controller using operational amplifier circuits.
6. Simulation of the Compensated System: Simulate the compensated system to verify that the design specifications are indeed satisfied.

Project 1 was assigned in Week 4. Due to the pandemic, many students found themselves balancing among multiple commitments (child care or work responsibilities), which impacted their ability to study and learn successfully [5]. To provide more guideline to the students, we clearly described when students would be ready to perform each task, as shown in Table 3.

Table 3. Project 1 Schedule

Step #	Topic	When am I able to do this?
1	Modeling of the original system	After we discuss how to obtain the transfer function of electrical circuits.
2	Simulation of the original physical circuits	If you want to use MultiSim or PSpice, you should be able to do this right away. If you want to use MATLAB Simulink (this is suggested), you should be able to do this after going through the "MATLAB Basics".
3	Analysis of the original system	After we discuss time response and performance specifications of a 2nd-order underdamped system.
4	Controller design	After we discuss root-locus-based PID controller design
5	Realization of the designed controller	
6	Simulation of the compensated system	Once the controller design is completed, this can be done immediately.

Project 2 involves Modeling and Control of a DC Motor. It was assigned after midterm. A permanent-magnet DC motor, as shown in Figure 2, was considered. The control tasks include design of an analog controller such that the motor's speed satisfies the given performance specifications (assuming that the load is zero). Students would further investigate the effect of load, which was assumed to be an unknown constant. Students would also investigate the effect of sampling on the digital control system.

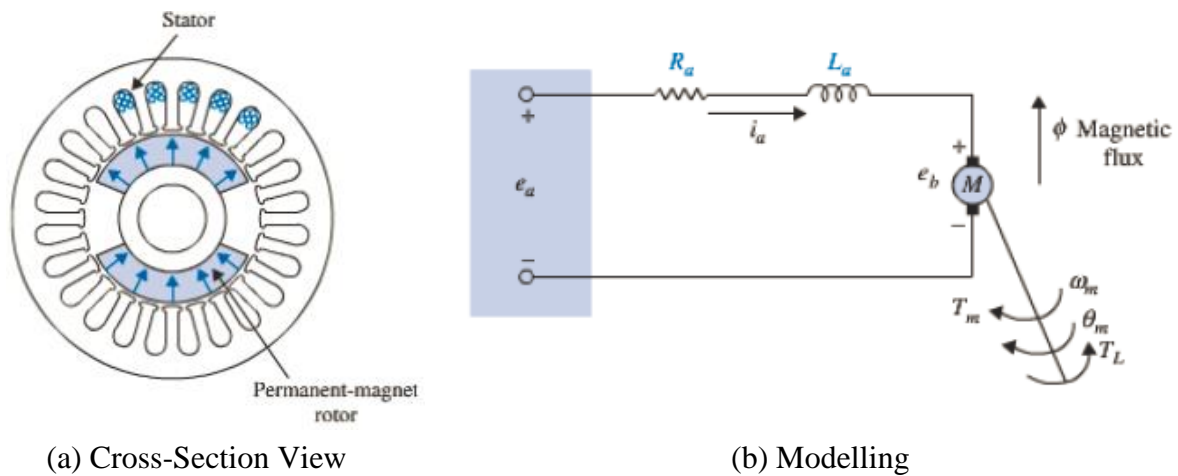(a) Cross-Section View   (b) Modelling
Figure 2. Modeling and control of a DC motor.

The typical steps of Project 2 are described below:

1. Modeling of the DC Motor.
2. Simulation of the DC Motor: Simulate the original system using MATLAB Simulink block "DC Motor", which represents the physical system. Compare the DC motor's speed with its Block Diagram representation to make sure that the modeling is correct.
3. Analysis of the Original System: Obtain the closed-loop transfer function in terms of both the voltage input and the load torque. Assuming that the load is 0, determine the settling time.
4. Analog Controller Design: Assuming that the load is 0, design an analog controller to satisfy the design specifications. Students were suggested to design a lead-PI controller so that the controller can be easily implemented using MATLAB Simulink.
5. Effect of Load: Investigate the effect of load by adding a load torque. For simplicity, suppose that the load is an unknown constant. Simulate the system to see if the steady-state error is affected or not.
6. Digital Control System: Suppose that the system is to be computer controlled (i.e., the analog controller is to be replaced by a digital controller). Obtain a digital controller using MATLAB command c2d () and then implement the digital controller using Simulink module "Discrete Transfer Function".

Results

Assessment of simulation projects & labs:

Table 4 provides the students' final grades when the Feedback and Control course was taught either with hardware-and-software-combined laboratory exercises or with simulation-only laboratory exercises. There were 16 students for hardware-and-software-combined and 27 students for simulation-only exercises.

Table 4. Distribution of Students' Final Grade

Final Grade	A and A-	B+, B, and B-	C+, C, and C-	D+ and D	F
When using hardware & software combined laboratory exercises	18.75%	43.75%	31.25%	0	6.25%
When using simulation-only laboratory exercises	11.1%	55.6%	18.5%	11.1%	3.7%

When students studied the course with combined laboratory exercises, 62.5% of the students received A/A- and B+/B/B- and one student failed the course. In the offering of the course using simulation-only laboratory exercises, the number of students who received A/A- and B+/B/B- was 66.7%. The number of students who failed the course was 1. It can be observed that the percentage of students whose grades are lower than C- is slightly increased (14.8% vs. 6.25%). We believe this is due to several factors: differences in time zones (since students were at home), less interaction between the instructor and the students, and less teamwork among the students. Despite these challenges, the grade distribution was in general comparable, indicating that the simulation-only laboratory exercises were able to help the students learn the concepts of feedback and control.

In addition to the course grades, observation of students' classroom participation during both lectures and lab sessions shows that students were reasonably engaged throughout the whole course. They answered the instructor's questions promptly, and actively shared their computer screens for demonstration and debugging. We will keep collecting data and monitoring students' learning performance should this course be offered online in the future.

Student feedback of simulation-only laboratory exercises:

A survey was conducted at the end of the summer 2020 semester to collect students' opinions about the simulation-only laboratory exercises. The survey questions, together with students' responses, are given in Figures 3~5, for the following three questions, respectively:

1) Simulation laboratory exercises increased my interest in the subject (Figure 3).
2) Simulation laboratory exercises helped me better to learn course content (Figure 4).
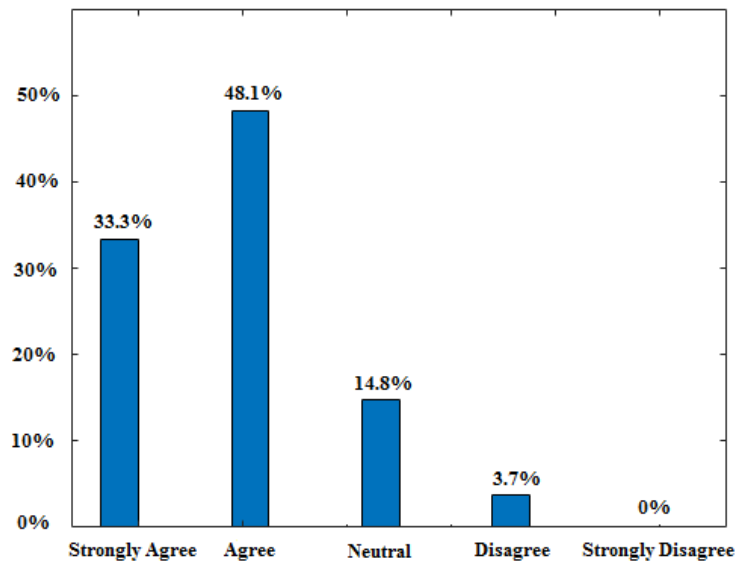3) What overall rating would you give simulation laboratory exercises (Figure 5).

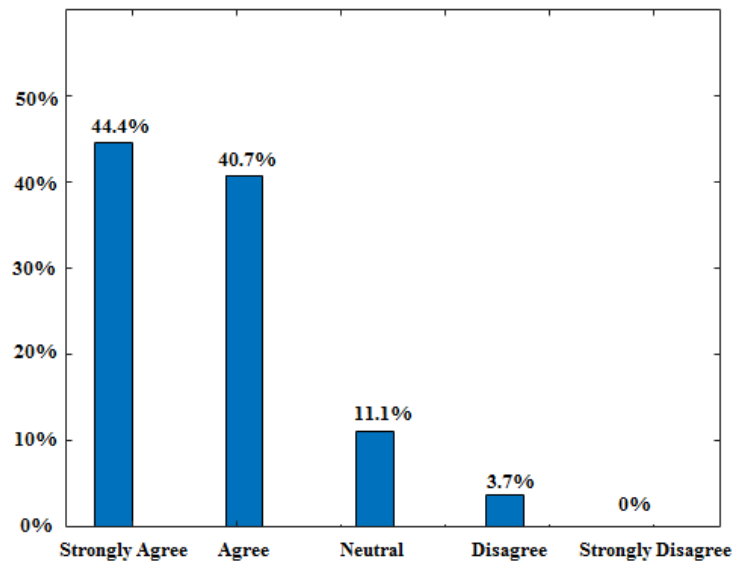Figure 3: Survey results for question "Simulation laboratory exercises increased my interest in the subject."

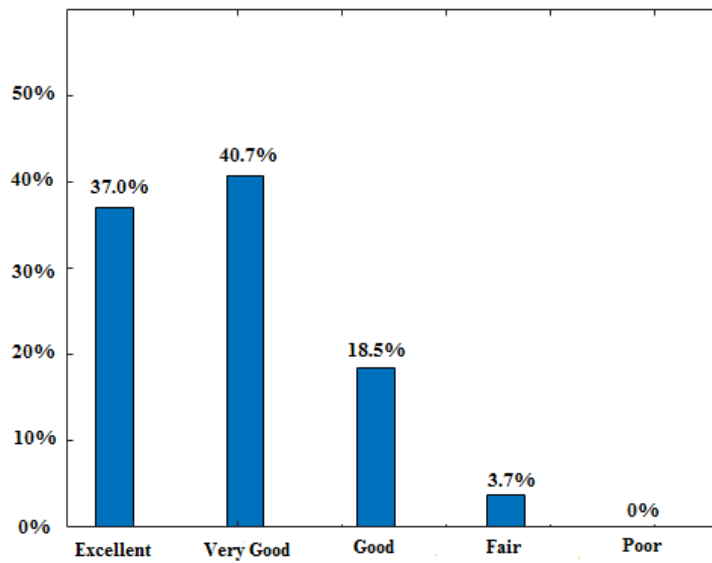Figure 4: Survey results for question "Simulation laboratory exercises helped me better to learn course content."

Figure 5: Survey results for question "What overall rating would you give simulation laboratory exercises."

Based on the survey, 81.4% of students "agree" or "strongly agree" that simulation laboratory exercises increased their interest in the subject (Figure 3), 85.1% of students "agree" or "strongly agree" that simulation laboratory exercises helped them better to learn course content (Figure 4), and 77.7% of the students thought simulation laboratory exercises were excellent or very good (Figure 5). These simulation-based labs & projects improve the entire teaching package of this undergraduate Feedback Control Course. Some of these computer labs and projects will potentially be used in future offerings under hybrid or in-person.

Discussion and Conclusions

Feedback and Control courses are usually considered to be abstract and mathematically involved. Many students have difficulty in relating the course subjects with their experience or gaining intuition. During the COVID-19 pandemic, the Feedback and Control course could have become even harder for some of the students who took the course under e-learning (distance learning, remote learning, online learning). To improve motivation and engagement of students during e-learning, a series of simulation-based labs and projects were used in the summer 2020 semester. Based on students' performance (final course grades) and positive feedback collected in a survey, simulation-only lab/project activities helped to maintain engagement and learning during the distance learning mode, even without the hands-on laboratory exercise, usually done in the on-campus lab. The simulation-only laboratory exercises helped students to understand the abstract concepts of Feedback and Control, including modeling, time response, stability, and root locus techniques, and etc.

To help students relate the abstract equations of feedback and control to the knowledge they already acquired from earlier courses, some of these activities were based on phenomena they were familiar with (such as electrical circuits and motors). By asking the students to make

measurements, tables, and graphs, students started to visualize the relations between familiar phenomena and new theories & equations. Some of these simulation based labs and projects may be used in future versions of the course to compliment the hands-on lab exercises.

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